The Effect of Gravitational Focusing on Annual Modulation

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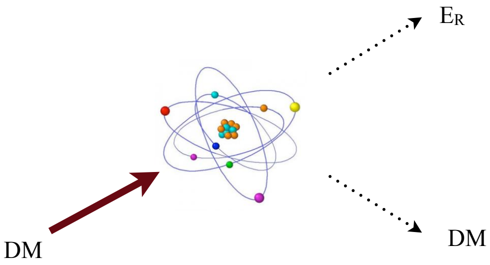
[1307.5323, 1308.1953]

Direct Detection

Dark matter scatters off of nuclei in detectors

Measure recoil energy of nuclei



Direct Detection

RAVE star survey

$v_{\rm esc} = [498, 608]$ km/s

Astrophysical Input

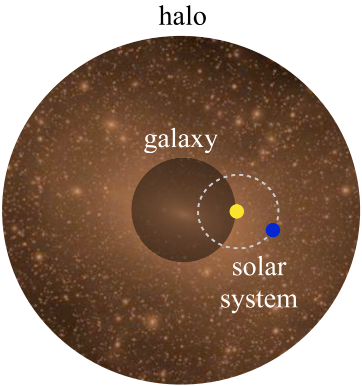
$$\frac{dR}{dE_R} \propto \int_{v_{\rm min}}^{v_{\rm esc}} d^3v \; \frac{d\sigma}{dE_R} \; v \; f(v)$$

Scattering kinematics

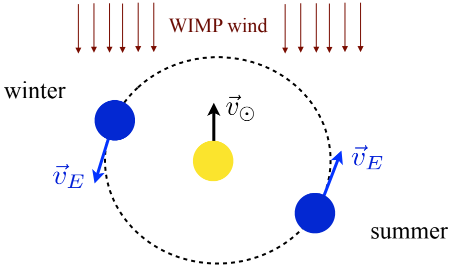
Model parameters

Annual Modulation

Dark matter signal modulates annually due to Earth's orbit about the Sun



(top-down view)



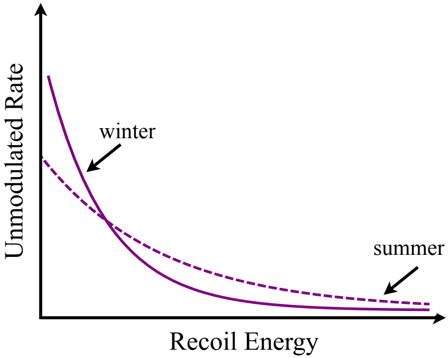
$$v \leq v_{\rm esc} + |\vec{v}_E - \vec{v}_\odot| \qquad v \leq v_{\rm esc} + |\vec{v}_E + \vec{v}_\odot|$$

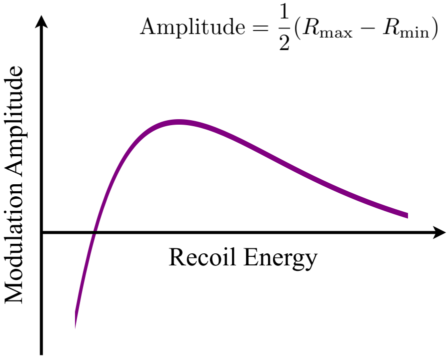
Drukier, Freese, and Spergel [PRD]
Review: Freese, **ML**, Savage [1209.3339]

Annual Modulation

More high-velocity particles in the summer, than the winter

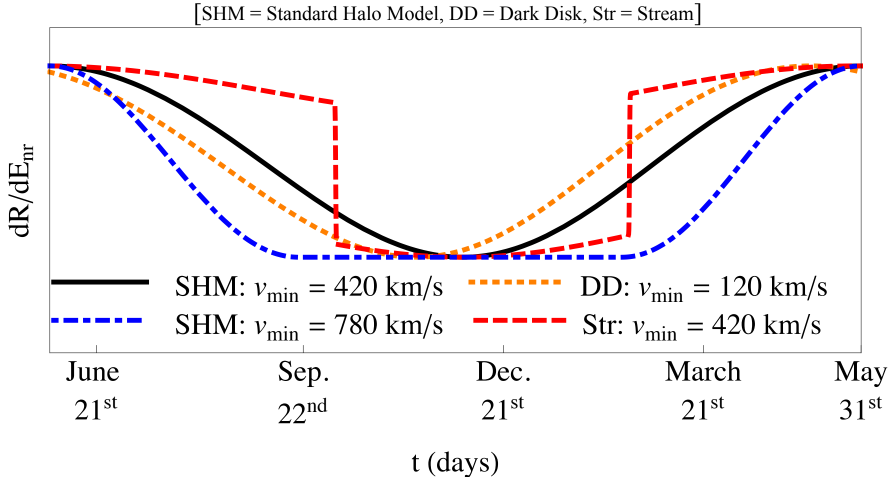
High-energy scattering events have a maximum ~June 1
Low-energy events have a maximum ~Dec 1





Modulation Spectrum

Shape of the modulation spectrum depends on assumptions about the particle and astrophysics properties



Higher Harmonics

Expand differential scattering rate in terms of Fourier components

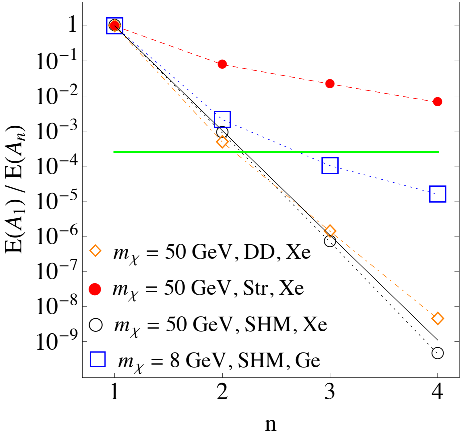
$$\frac{dR}{dE_{\rm nr}} = A_0 + \sum_{n=1}^{\infty} \left[A_n \cos n\omega(t - t_0) + B_n \sin n\omega(t - t_0)\right]$$

Relative strength of higher Fourier modes enhanced for

- high v_{min} scenarios (i.e., light or inelastic DM)
- local DM substructure in the halo

Higher Harmonics

$E(A_1)/E(A_n) =$ Exposure needed to observe A_1 to 95% confidence, relative to that for A_n



[SHM = Standard Halo Model, DD = Dark Disk, Str = Stream]

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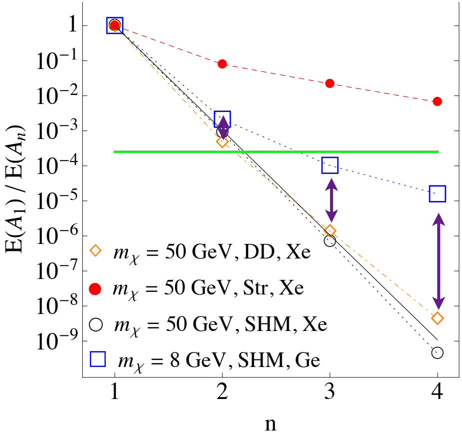

Less exposure needed to observe the higher-frequency modes for light dark matter

[SHM = Standard Halo Model, DD = Dark Disk, Str = Stream]

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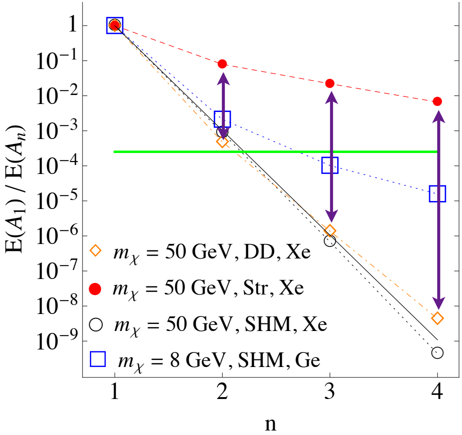


Less exposure needed to observe the higher-frequency modes for light dark matter

High-frequency modes very enhanced for dark matter streams

[SHM = Standard Halo Model, DD = Dark Disk, Str = Stream]

Higher Harmonics

Predicted amount of time to observe higher-harmonic modes for CDMS-Si best-fit point

$m_\chi = 8.6\ \text{GeV}, \sigma_0 = 1.9 \times 10^{-41}$

Mode	**XENON1T** E_{thresh}: 4 keV_{nr}	**GEODM DUSEL** 5 keV_{nr}	**GEODM DUSEL** 2 keV_{nr}
A_1	≤ 1 year	≤ 1 year	≤ 1 year
A_2	≤ 1 year	≤ 1 year	≤ 1 year
B_1	-	-	1 - 2 years
B_2	-	-	-
A_d	-	-	2 - 3 years

A particular example:

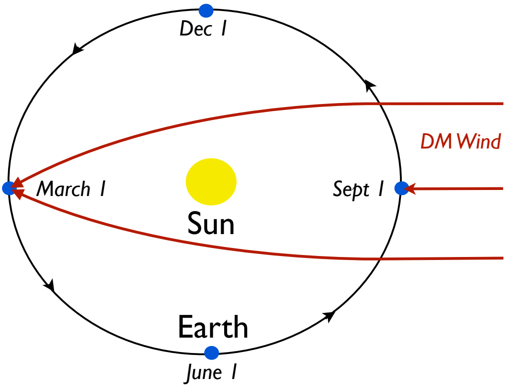
Gravitational focusing of dark matter particles

affects B_1 mode (modulation phase)

Gravitational Focusing

Sun's potential deflects incoming, unbound dark matter particles

Focusing effect is strongest during the Spring

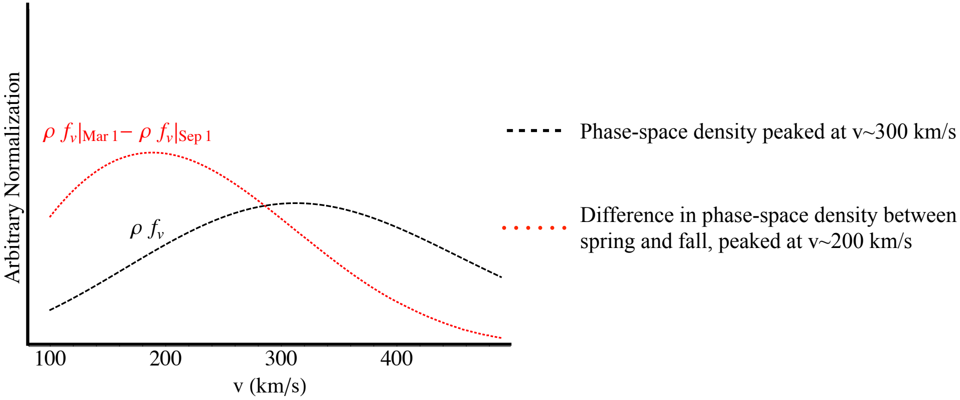


K. Griest, PRD 1988.
Alenazi and Gondolo [astro-ph/0608390]

Phase-Space Density

Define phase-space density in the lab frame at time *t* to be

$$\rho f_v|_t \equiv \rho \int d\Omega \; v^2 f(\mathbf{v}, t)$$



Modulation Phase

Earth's orbit causes ~3% modulation that is extremized ~June 1

Focusing causes ~1.5% modulation that is peaked ~March 1

$v_{\min} \gtrsim 200~\mathrm{km/s}$ Modulation due to Earth's orbit dominates

$v_{\min} \sim 200~\mathrm{km/s}$ Gravitational focusing starts to become important

$v_{\min} \lesssim 200~\mathrm{km/s}$ Focusing causes phase to shift towards March 1

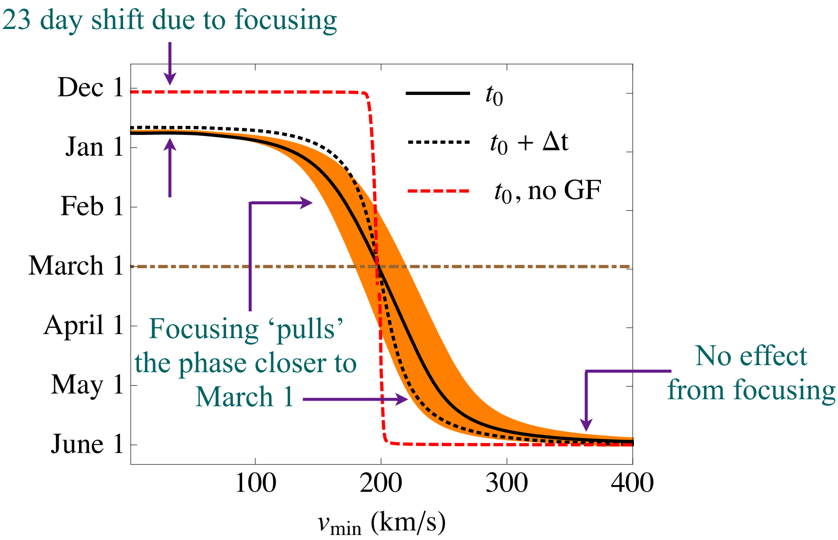
Shift due to higher-frequency modes

$$\frac{dR}{dE_{\mathrm{nr}}} \approx A_0 + A_1 \cos\omega(t - t_0 - \Delta t)$$

Maximum of rate

Modulation Phase

$$\frac{dR}{dE_{\rm nr}} \approx A_0 + A_1 \cos\omega(t - t_0 - \Delta t)$$



Experimental Implications

Minimum scattering velocity depends on the mass of the dark matter, as well as the target nucleus

Mass of target nucleus

$$v_{\mathrm{min}} = \sqrt{\frac{m_n E_{\mathrm{nr}}}{2\mu^2}}$$

Recoil energy of nucleus

Reduced mass of nucleus and dark matter

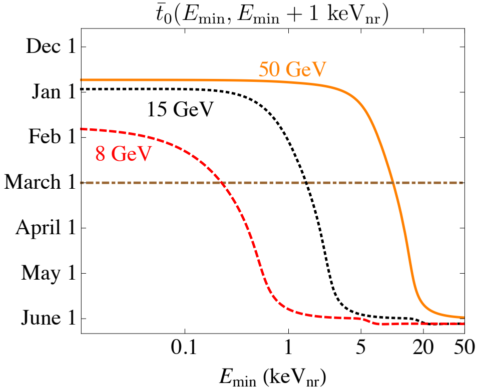
Lower v_{min} for heavier dark matter

Lower v_{min} for lighter dark matter at lower recoil energy

Example: Ge Target

For current thresholds, phase shift particularly significant for masses greater than ~15 GeV

Current advances in low-threshold technology could make shift relevant for ~8 GeV dark matter



Scattering rate in finite energy bin:

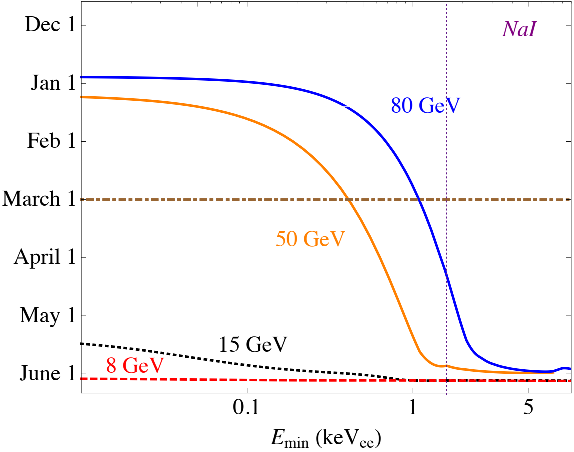
$$\bar{R}(E_{\rm min}, E_{\rm max}) = \int_{E_{\rm min}}^{E_{\rm max}} dE_{\rm nr} \frac{dR}{dE_{\rm nr}}$$

$\bar{t}_0$ is the time of maximal $\bar{R}$

DAMA

NaI(Tl) target, claims 9.3σ modulation

Can correspond to ~10 or 80 GeV dark matter
Both in tension with null results from other experiments



DAMA

80 GeV scenario affected by gravitational focusing

The phase shift can be as much as a ~month in the low-energy bins

	2-2.5 keV_{ee}	**2-3 keV_{ee}**	**2-4 keV_{ee}**	**2-5 keV_{ee}**	**2-6 keV_{ee}**
DAMA, measured	?	?	May 12±7	May 22±7	May 26±7
80 GeV (w/GF)	**April 29**	**May 10**	May 19	May 21	May 22

Gravitational focusing results in a dependence of phase on recoil energy bin

Can be used to distinguish signal from background

Conclusions

Particle and astrophysics assumptions about dark matter can enhance higher-frequency modes of modulation spectrum

Unbound dark matter particles focused by Sun's gravitational potential, affecting the modulation phase

Phase shift most relevant for low-v_{min} particles

i.e., masses greater than ~15 GeV, or lighter mass particles at low-threshold experiments